06/23/11

Towards a Compelling Physics Case for a Future eRHIC

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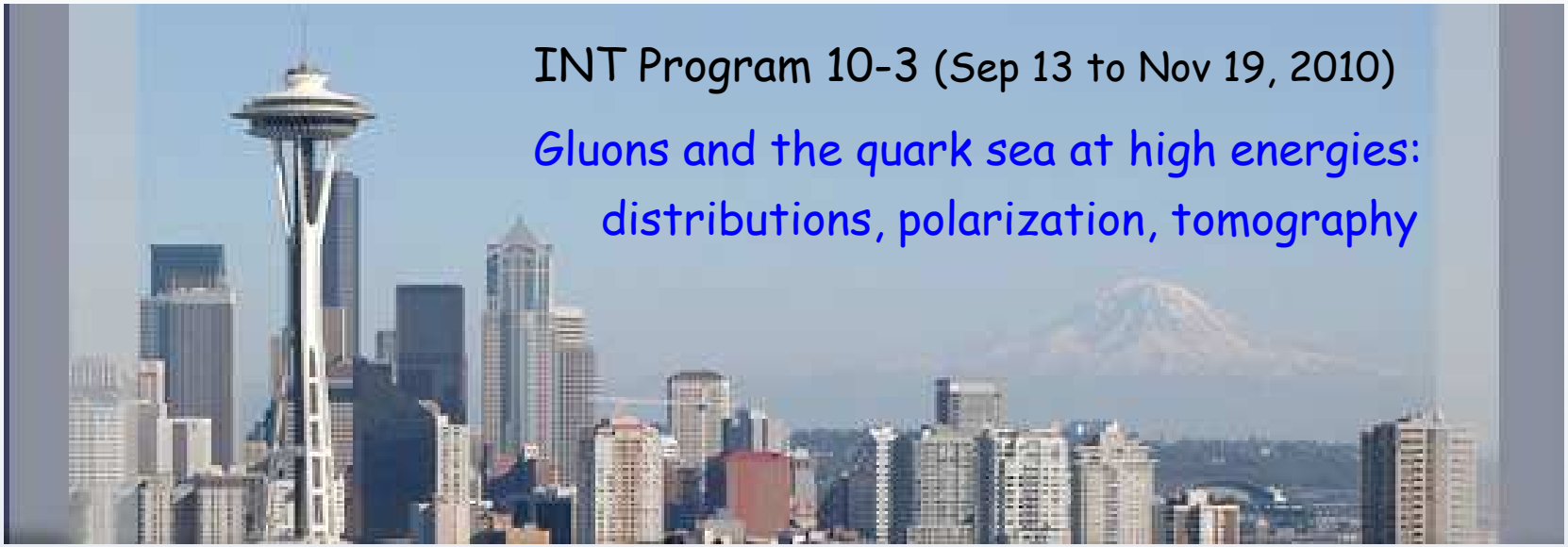


INT Program 10-3 (Sep 13 to Nov 19, 2010)

Gluons and the quark sea at high energies: distributions, polarization, tomography

organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

strong BNL involvement

convenors: D. Hasch, M.S., F. Yuan *spin & PDFs*

M. Burkardt, V. Guzey, F. Sabatie *imaging*

A. Accardi, M. Lamont, C. Marquet *eA*

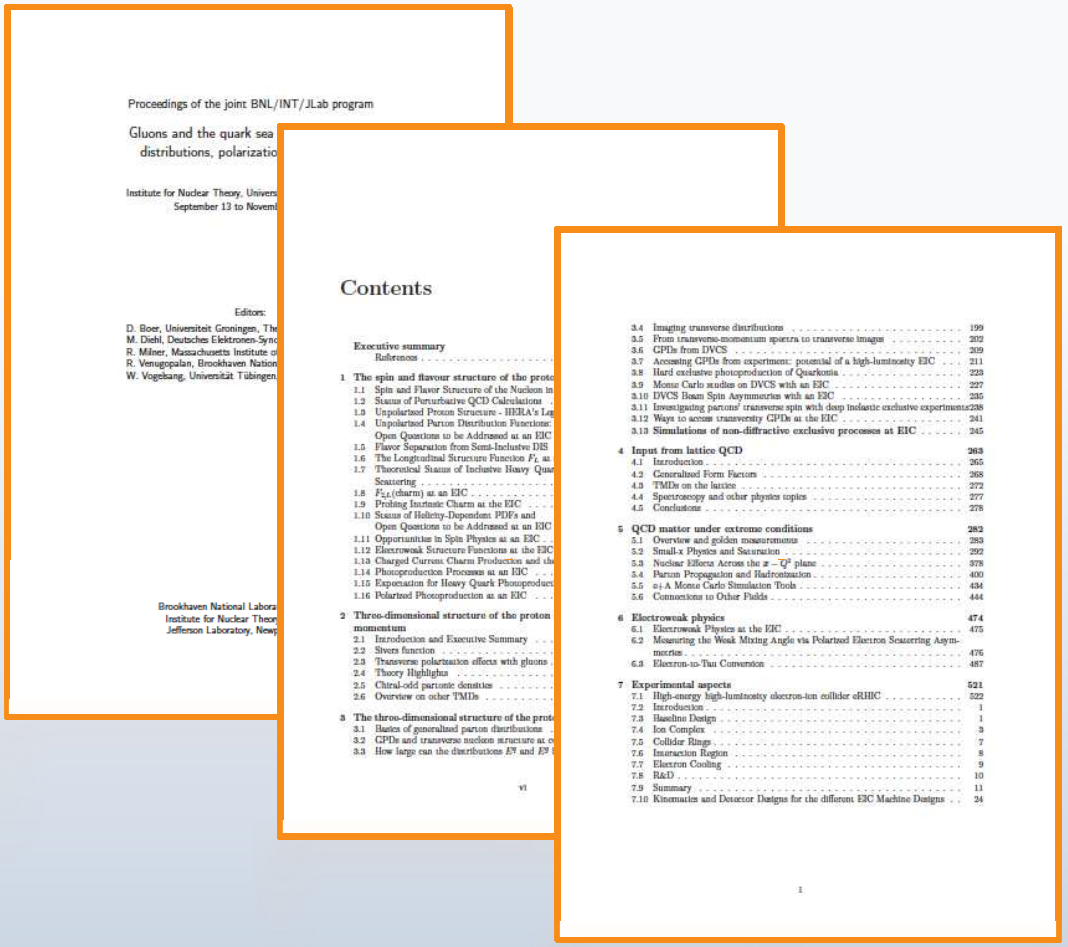
K. Kumar, Y. Li, W. Marciano *beyond SM*

main goal: sharpen the physics case for an EIC for next NSAC long range plan

- identify outstanding open questions in hadronic physics still relevant in 10+ years
- devise key "golden" measurements in ep and eA to address these questions
- quantify experimental needs & requirements and study feasibility

very successful, well attended program; most goals accomplished

detailed 500+ pages write-up is in its finishing stages – to appear on the arXiv soon


Proceedings of the joint BNL/INT/JLab program

Gluons and the quark sea

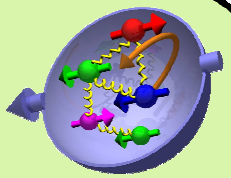
Contents

but no time to sit & relax

- studies for identified **"golden measurements"** need to be substantiated & feasibility demonstrated
- input for community wide white paper (draft by end of 2011)

most compelling physics questions

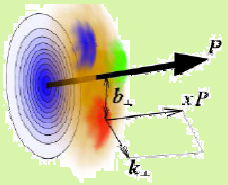
spin physics



- what is the polarization of gluons at small x where they are most abundant
- what is the flavor decomposition of the polarized sea depending on x

determine quark and gluon contributions to the proton spin at last

imaging

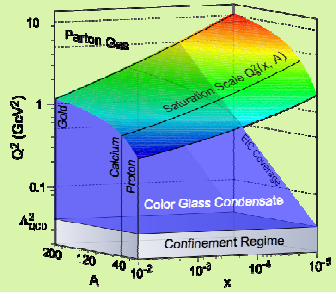


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by k_T dep. distr'n

possible window to orbital angular momentum

physics of strong color fields

quantitatively probe the universality of strong color fields in AA, pA, and eA

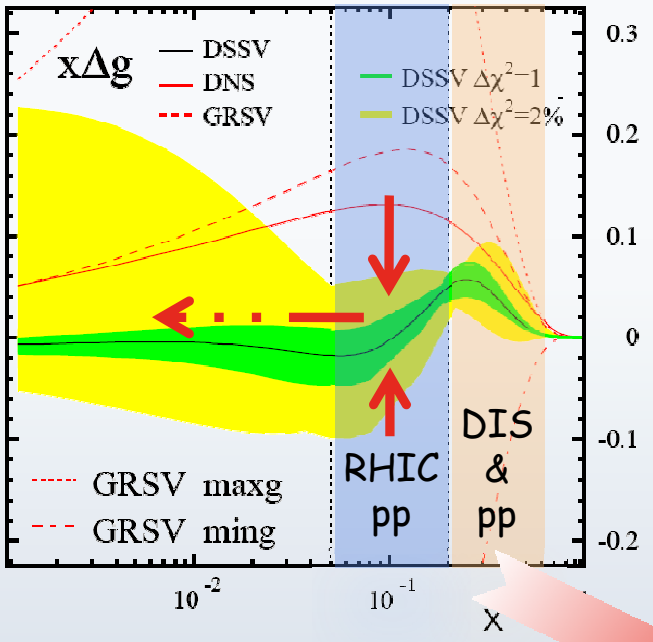


- understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- how do hard probes in eA interact with the medium

Selected "golden" Measurements

the quest for the spin of the proton: Δg

current status:



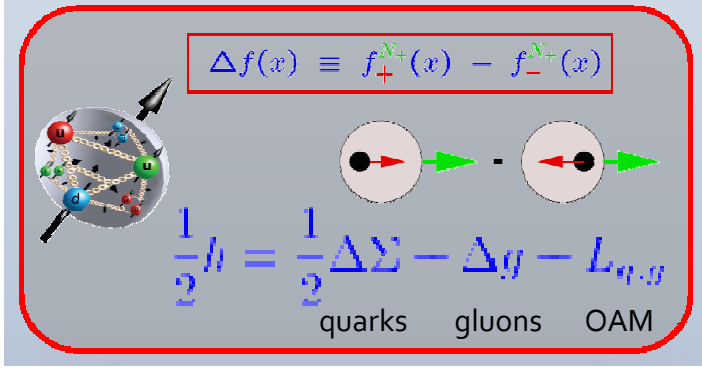
DSSV global fit
de Florian, Sassot,
MS, Vogelsang

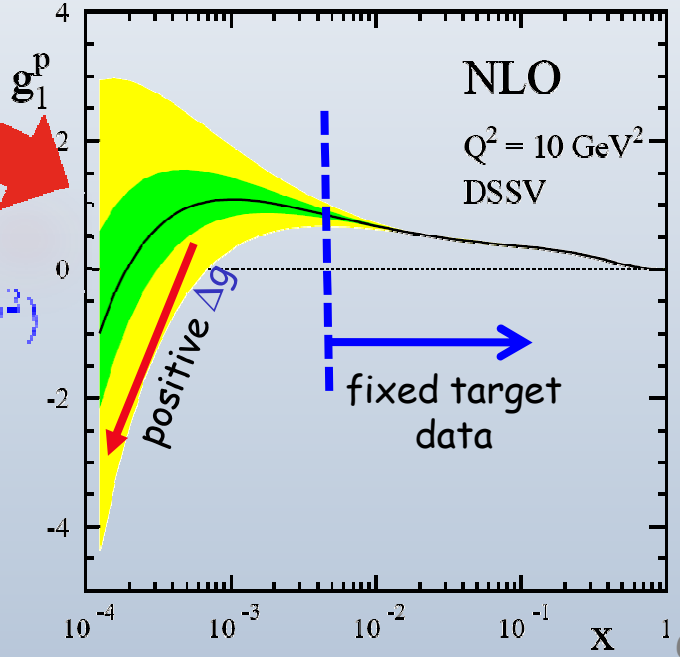
- low x behavior unconstrained
  significant polarization still possible
- no reliable error estimate
  for 1st moment $\int_0^1 dx\, \Delta g(x, Q^2)$
  (enters spin sum rule)
- RHIC will continue to improve
  our knowledge at medium x

best probe for small x gluons

pQCD scaling violations

$$\frac{dg_1(x, Q^2)}{d \ln Q^2} \propto -\Delta g(x, Q^2)$$





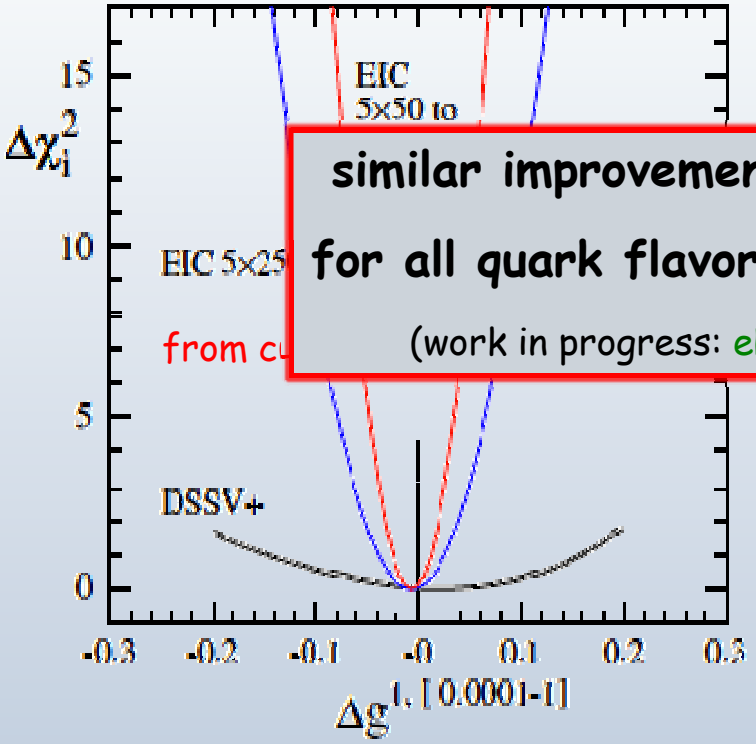
what can be achieved for Δg at eRHIC

how effective are scaling violations ?

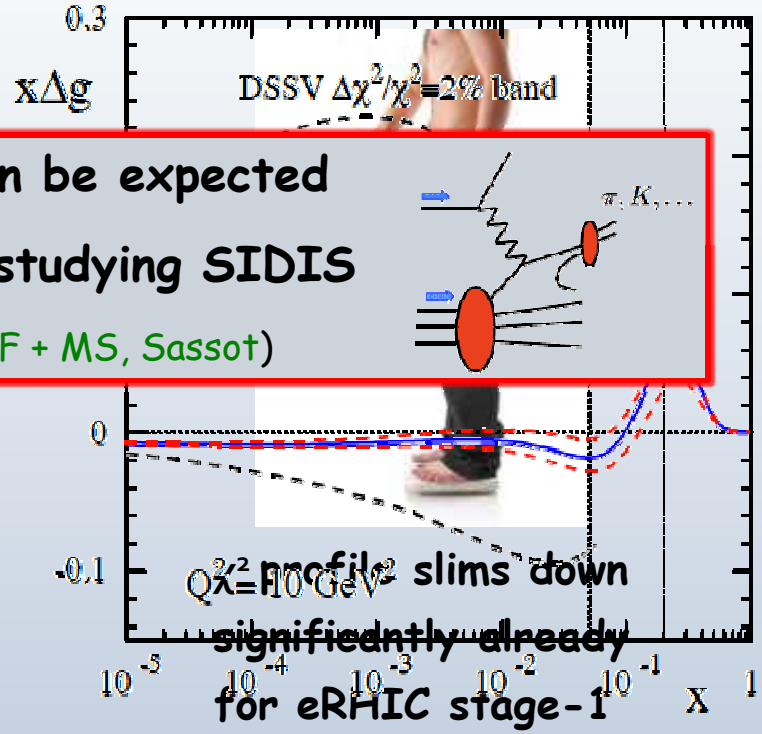
Sassot, MS

quantitative studies based on simulated data for stage-1: 5 x (50, 100, 250, 325) GeV

χ^2 profile for $\int_{10}^{1} \Delta g(x, Q^2)\, dx$



uncertainties on the x-shape of $\Delta g(x, Q^2)$



similar improvements can be expected

for all quark flavors by studying SIDIS

(work in progress: eRHIC TF + MS, Sassot)

χ^2 profile slims down significantly already for eRHIC stage-1

expect to determine $\int_0^1 dx\, \Delta q(x, Q^2)$ at about 10% level (or better – more studies needed)

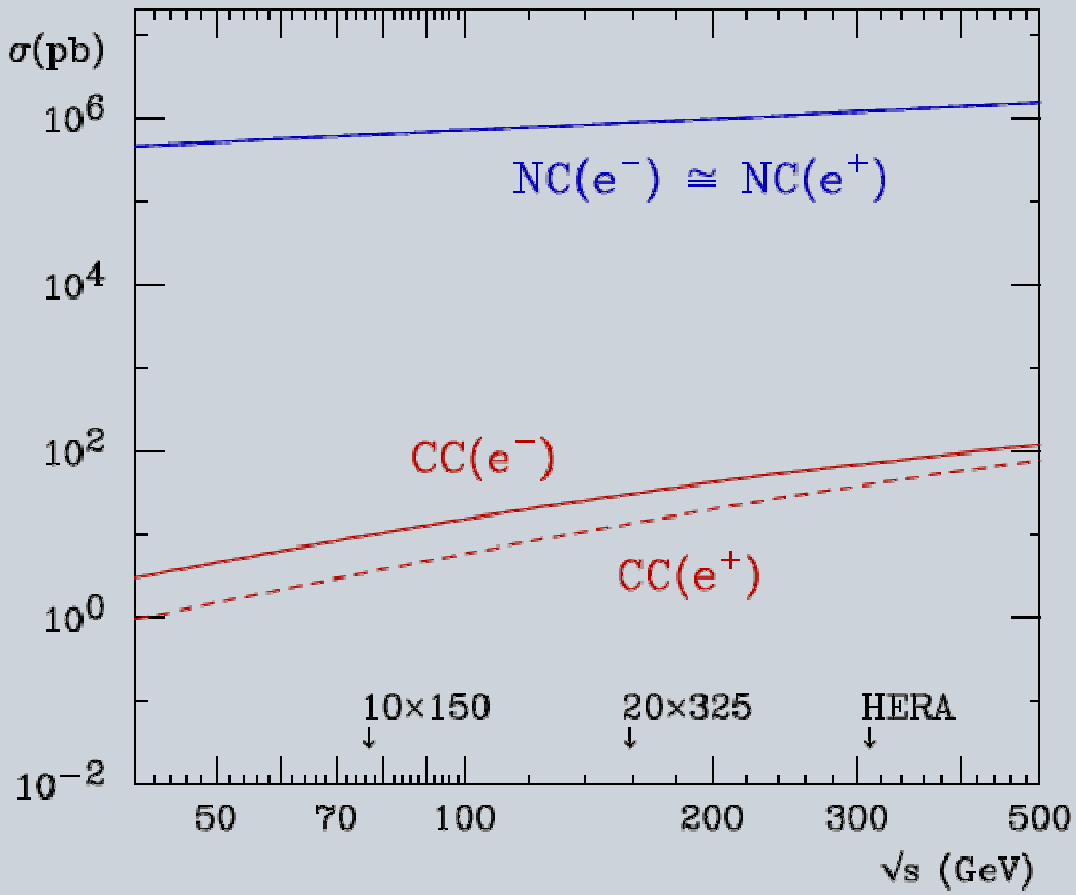
kinematic reach down to x = 10^{-4} essential to determine integral

large Q^2: novel electroweak probes for Δq's

aneja, Vogelsang

key for e-w measurements at eRHIC:

drop in cross section more than compensated by luminosity increase



vant

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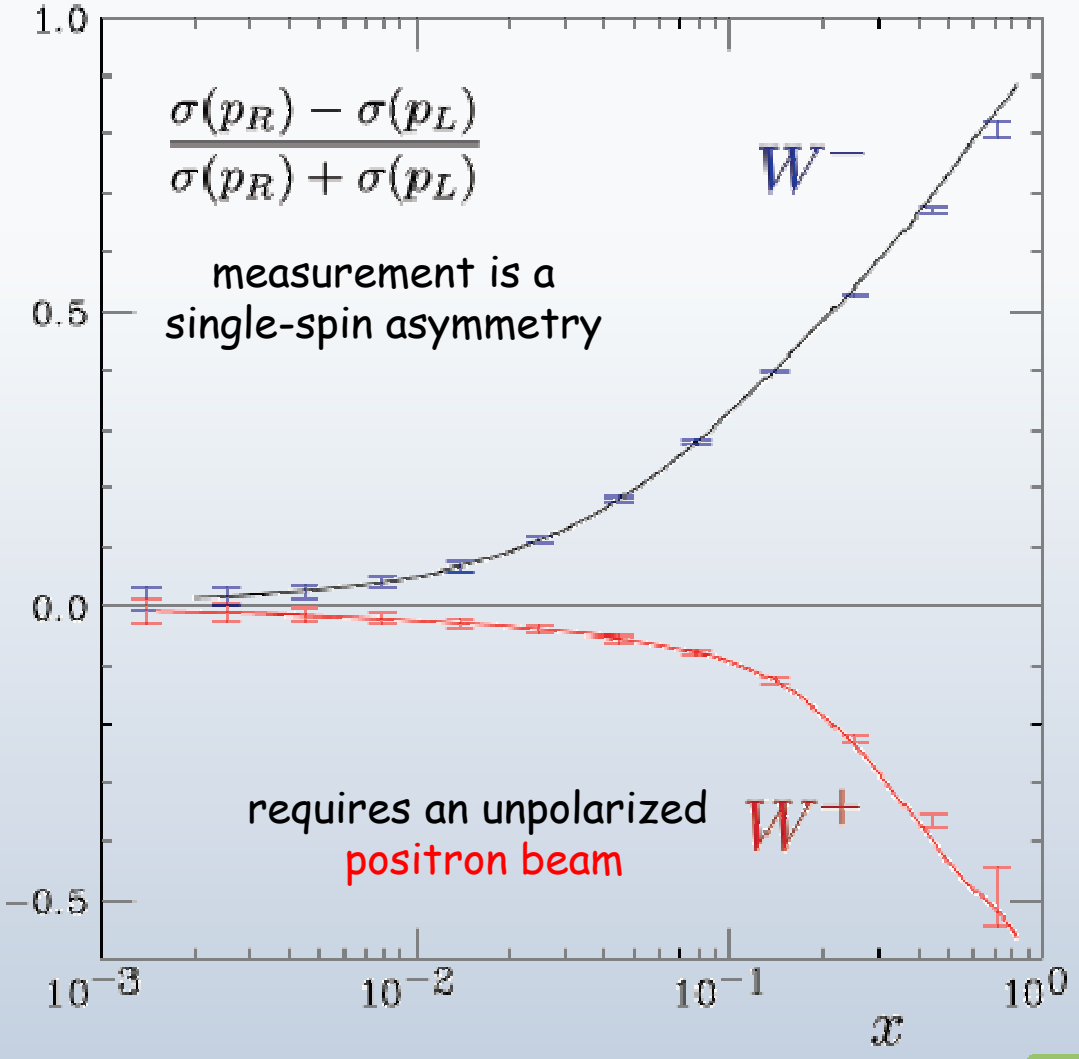
hadron-s

hadron-s

Vogelsang;
owski;
ano, Ridolfi; …

unexplored so far – unique opportunity for the EIC

most promising: charged current DIS



20 250 GeV

DIS cuts

10 fb^{-1}

need to be able to reconstruct x, Q^2 from hadronic final-state

separate up-type and down-type PDF combinations by varying y

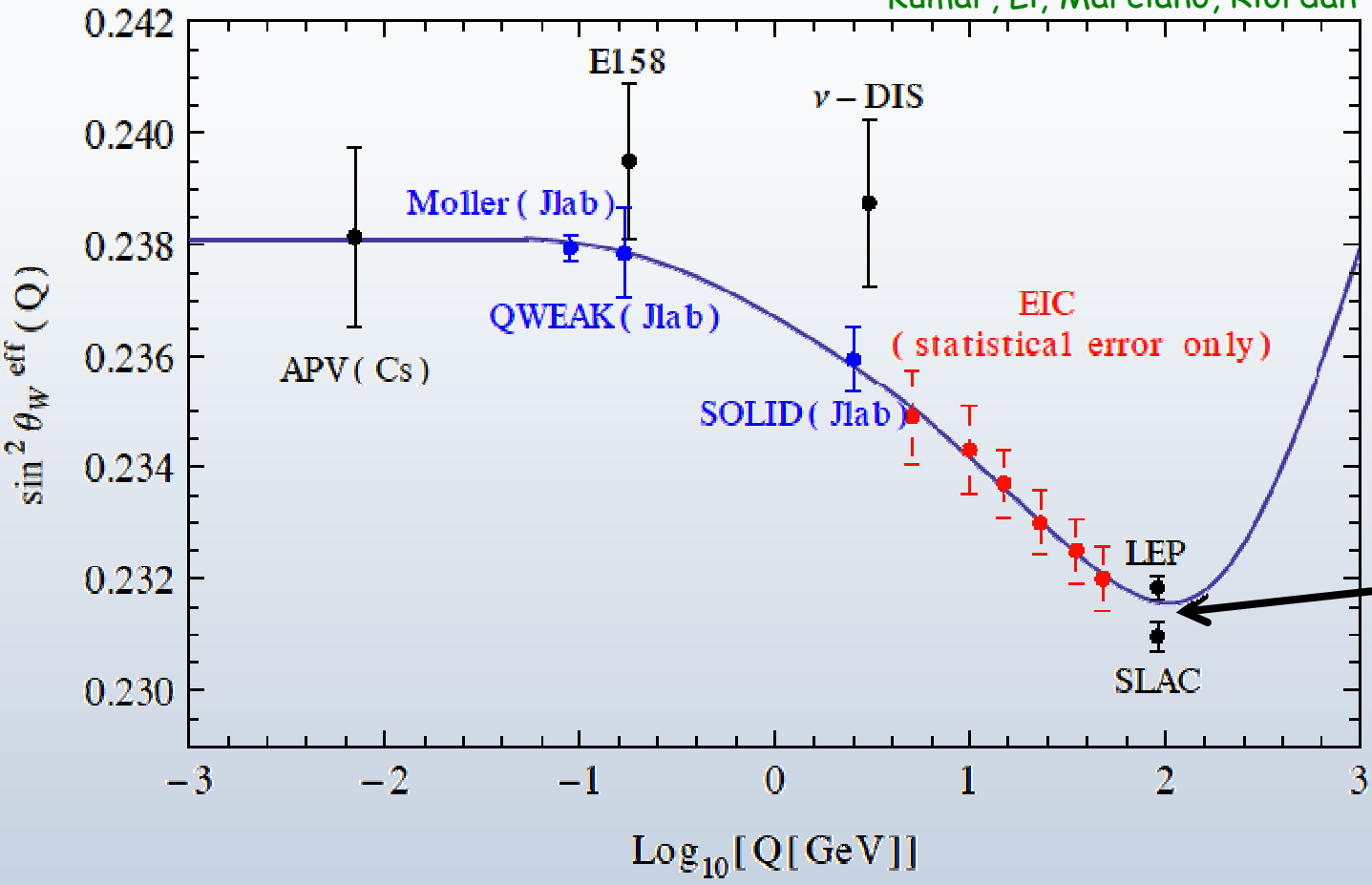
$$A^{W^-} \quad \frac{(\Delta u + \Delta c) \quad (1 \quad y)^2(\Delta \bar{d} + \Delta \bar{s})}{(u + c) + (1 \quad y)^2(\bar{d} + \bar{s})} \qquad A^{W^-} = \frac{(1-y)^2(\Delta d + \Delta s) \quad (\Delta \bar{u} + \Delta \bar{c})}{(1-y)^2(d + s) + (\bar{u} + \bar{c})}$$

Cabibbo suppressed contributions neglected

aside: electroweak precision physics at eRHIC ?

- goal: measure running of $\sin^2 \Theta_W$ over a wide range of scales Q

Kumar, Li, Marciano, Riordan



statistical errors only
assumes 200 fb^{-1} at
20 x 250 GeV

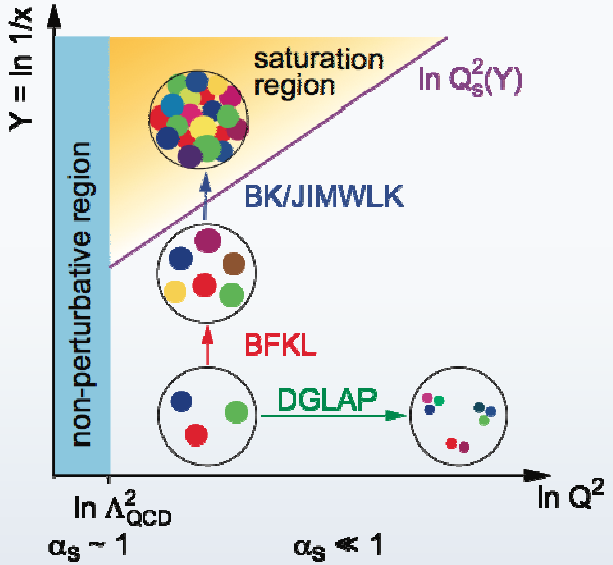
apparent discrepancy
at Z pole (3 sigma)

different implications
for new physics

- other avenues pursued: electron-tau conversion

Deshpande, Faroughy, Gonderinger, Kumar, Taneja

saturation in eA DIS – what to expect

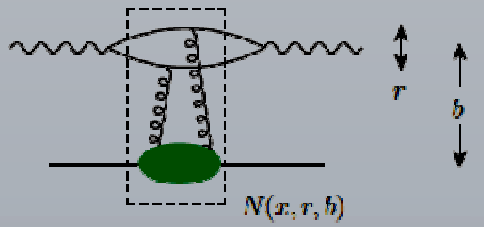


gluons in nucleus: terra incognita

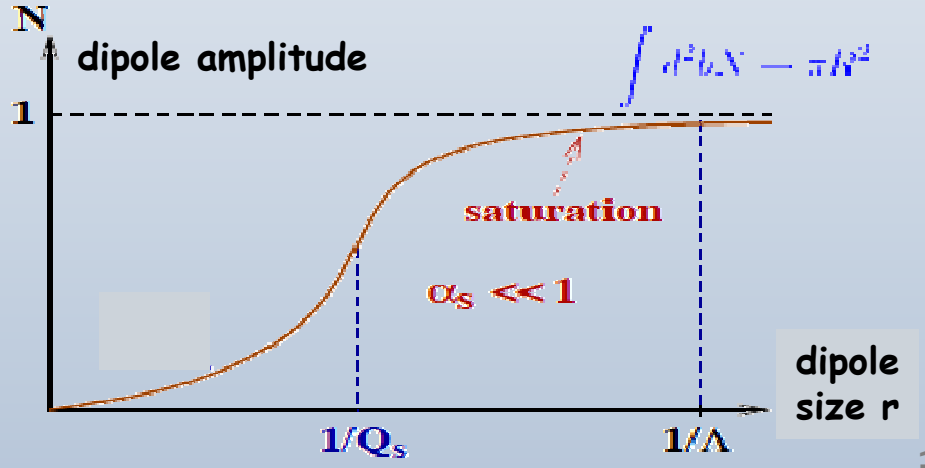
- **at high energy/small x:** transition to non-linear regime of strong gluon fields; DGLAP fails
- physics in **saturation regime** controlled by dynamical semi-hard scale $Q_s(x,A)$
- 1st hints for saturation at $x \approx 10^{-3}$ from RHIC forward hadrons in dAu

estimate relevance of non-linear effects from average strength of dipole scattering in DIS

recall: DIS in the proton rest frame: photon splits into a quark-antiquark pair ("**color dipole**") which scatters off the target proton (= "slow" gluon field)



$$\sigma^{\gamma^* p}_{T,L}(x,Q^2) = \int d^2r\, dz\, |\Psi_{T,L}(z,\mathbf{r},Q^2)|^2\, d^2b\, N(x,\mathbf{r},\mathbf{b})$$

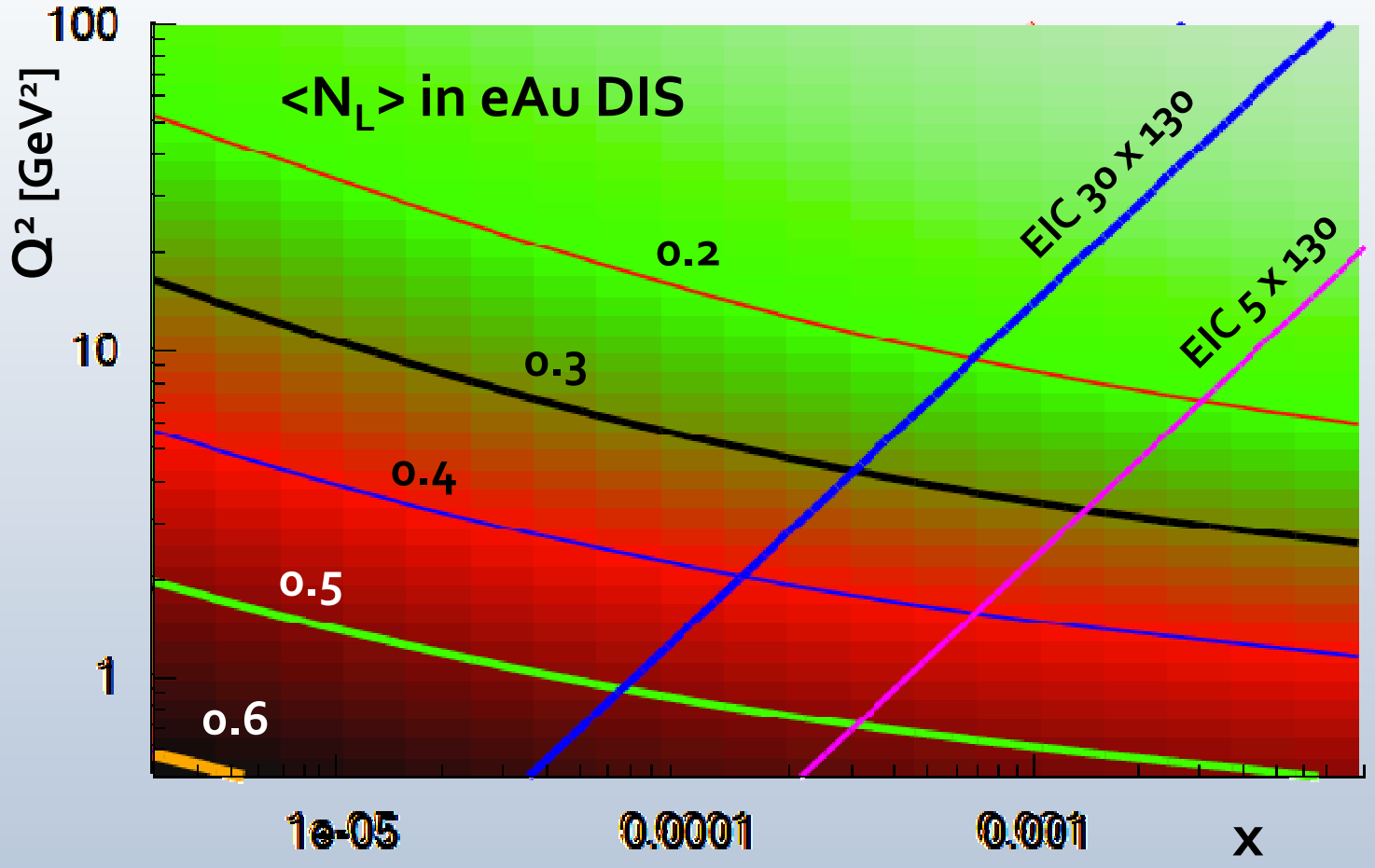


saturation in eA DIS – cont'd

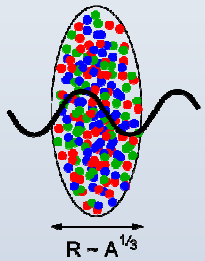
quantitative estimates

M. Diehl, T. Lappi

- find: $\sigma_L^{\gamma^*}(x,Q^2) \propto F_L(x,Q^2)$ most sensitive to gluons
- as expected (HERA data): no chance in ep
- eA much more favorable to study saturation than ep



saturation effects in eA benefit from nuclear oompf

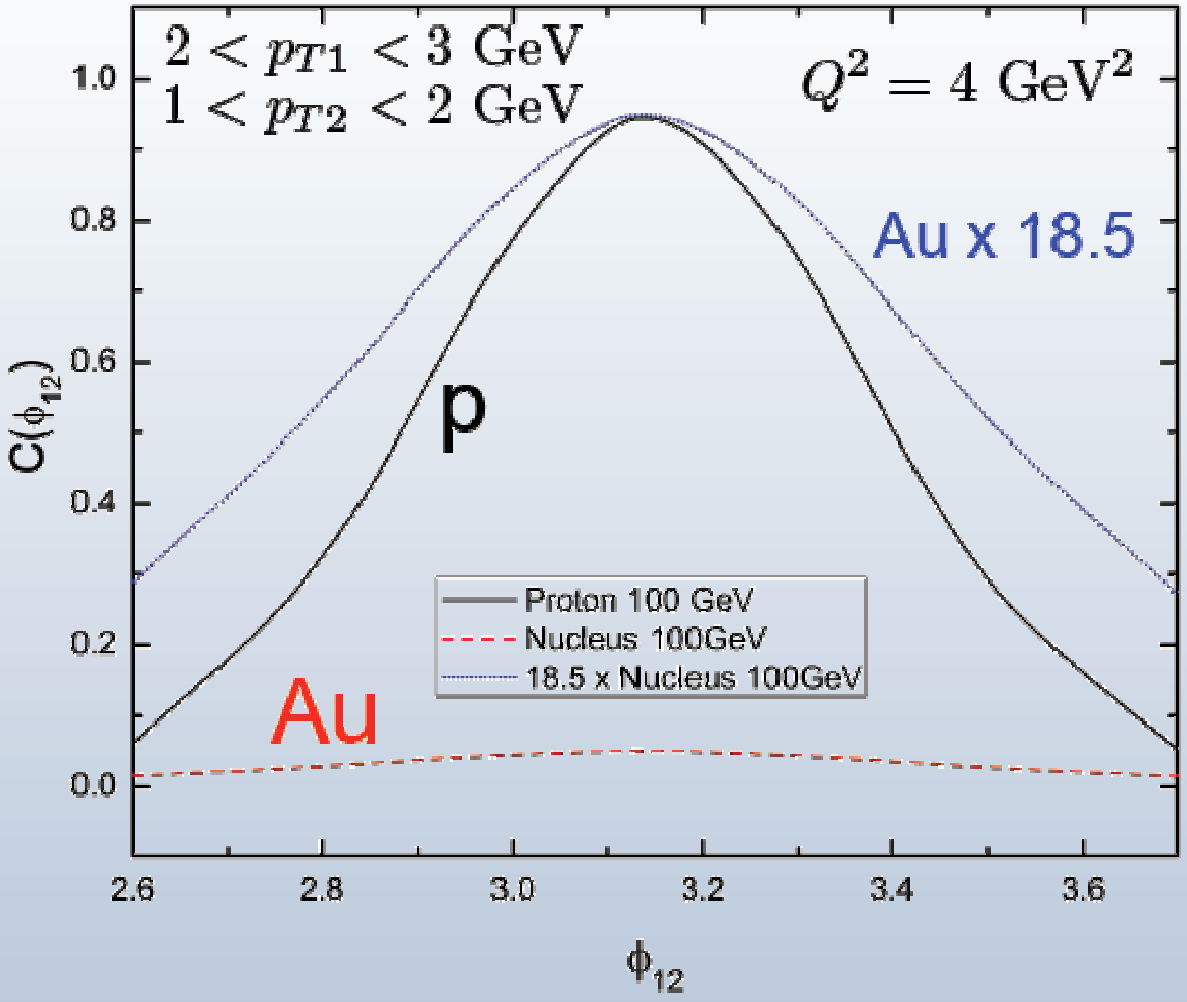


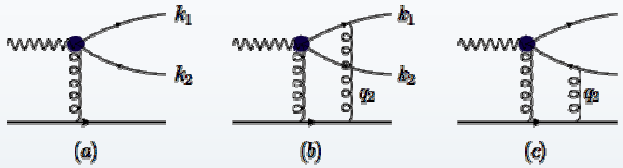
$$Q^2_{s,A} = A^{1/3} Q^2_{s,p}$$

di-hadron correlations in eA

never been measured before; **excellent signature for saturation in eA**

Dominguez, Xiao, Yuan





systematic depletion of away-side peak with increasing nuclear size/energy

can be also obtained in TMD factorization <-> unintegrated gluon at small x

hadronization in eA

physics objectives: understand quantitatively medium effects such as parton energy loss, p_T broadening, hadron absorption, …

typical observable: multiplicity ratios for ep vs. eA R_A^h

$$\frac{N_A^h(Q^2,\nu,z,P_T^2)/N_A^{DIS}(Q^2,\nu)}{N_p^h(Q^2,\nu,z,P_T^2)/N_p^{DIS}(Q^2,\nu)}$$

advantage: dependence on nuclear PDFs largely drops out

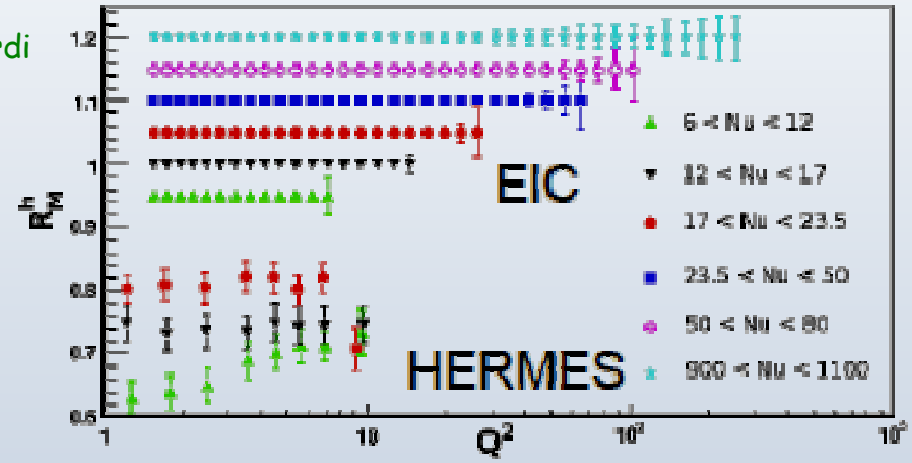
recent NLO study
Sassot, MS, Zurita

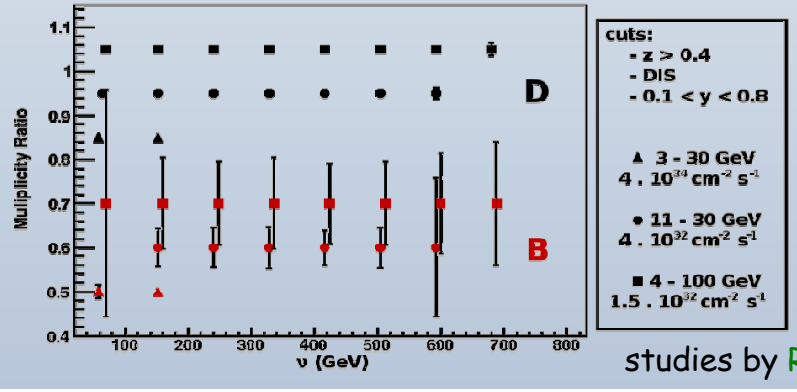
- **hadron attenuation** studies by R. Dupre, A. Accardi

  vastly extended reach in $\nu = q \cdot P/M$

  can "dial" ν to control characteristic path length in medium

  allows for detailed studies of energy loss, …





studies by R. Dupre, A. Accardi

- **heavy quark propagation & energy loss**

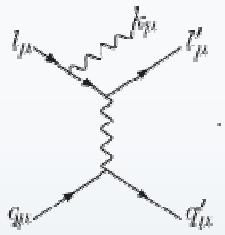
  never studied in eA

  quark mass dependence of energy loss

complication: QED radiative corrections

precision measurements in ep/eA require good understanding of QED corrections

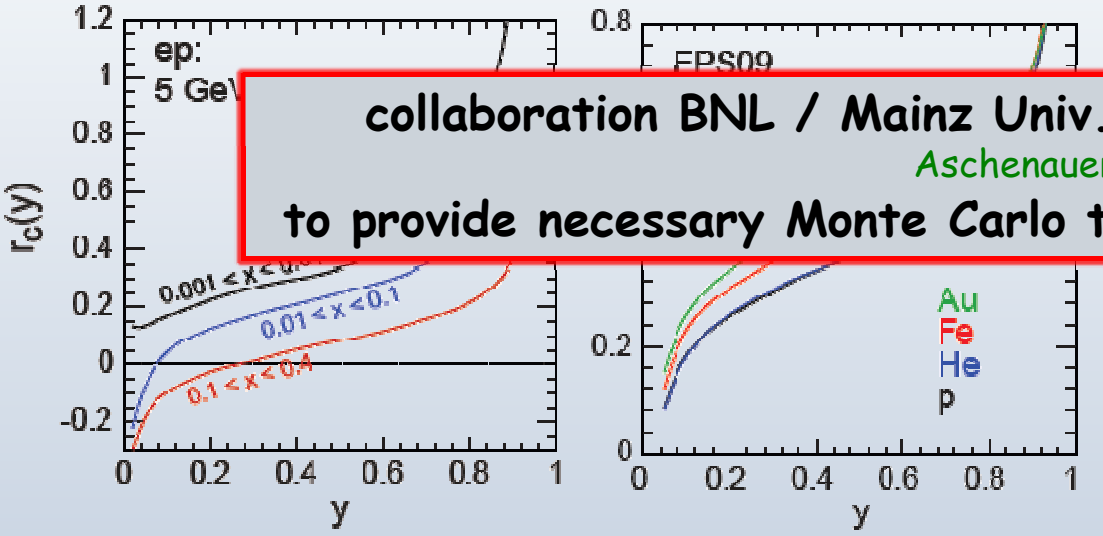
problem:



photon radiation strongly affects exp. determination of kinematics

e.g. $Q^2 = -(l - l')^2 \rightarrow \bar{Q}^2 = -(l - l' - k)^2$

effects are large but we can benefit from HERA experience



"correction factor"

$\frac{\sigma(\ldots)}{\ldots} - 1$

collaboration BNL / Mainz Univ. planned

Aschenauer, Spiesberger, MS

to provide necessary Monte Carlo tools & studies

H. Spiesberger

extraction of "true" structure functions requires unfolding procedure:

$$F_i^{obs}(x, Q^2) = \int dx d\bar{Q}^2 \, R_i(x, Q^2; \bar{x}, \bar{Q}^2) \, F_i^{true}(\bar{x}, \bar{Q}^2)$$

"radiator function"
calculable

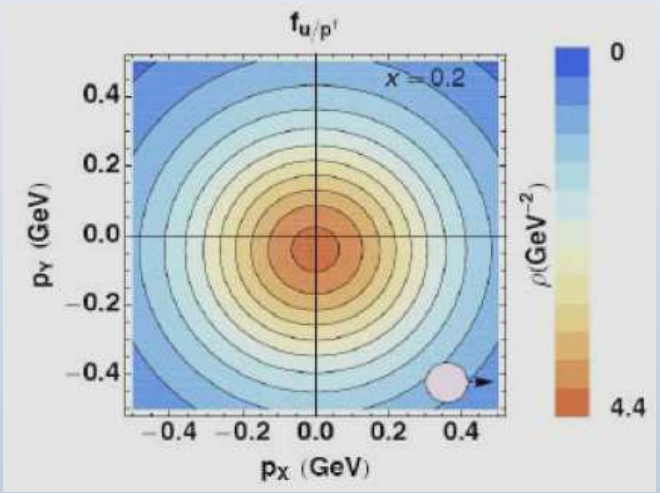
"3D imaging" of nucleons and nuclei

goal: going beyond longitudinal momentum structure & collinear factorization

TMDs

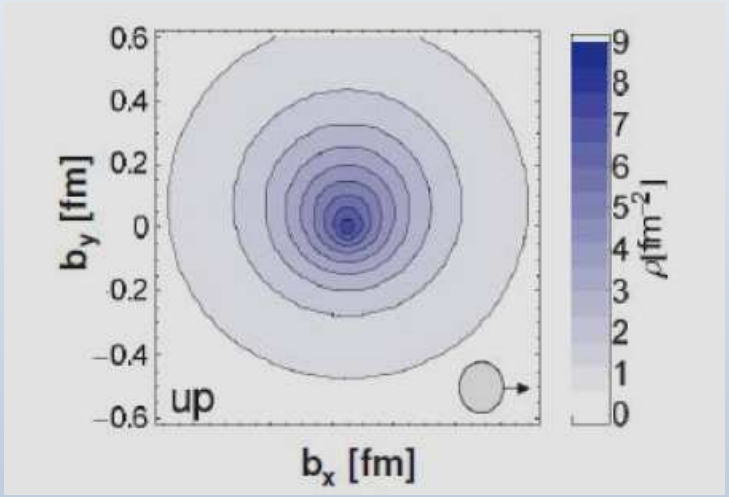
GPDs

2+1 D picture in **momentum space**



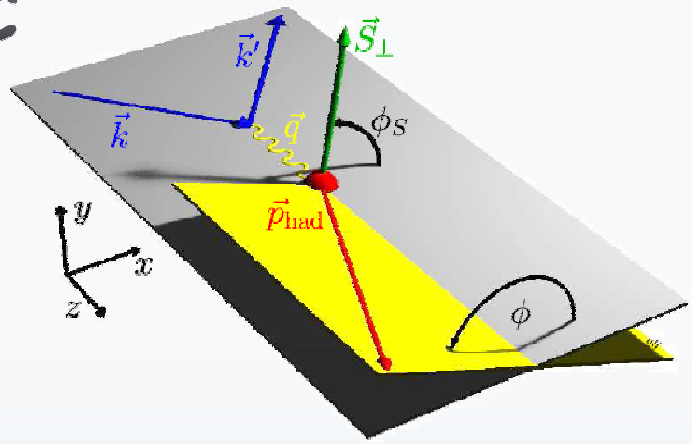
Bacchetta, Conti, Radici

2+1 D picture in **impact-parameter space**



QCDSF collaboration

TMDs @ eRHIC



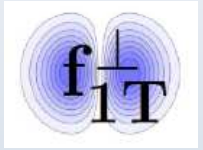
suite of observables accessible in

azimuthal (ϕ) asymmetries in SIDIS

related to entire zoo of TMD functions
measured at large x by HERMES & COMPASS

focus on unpolarized f_1 and Sivers function to illustrate underlying physics:

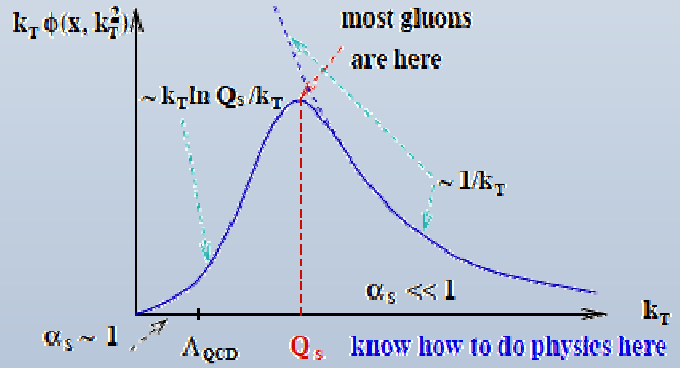
$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S}\cdot(\hat{\mathbf{P}}\times\mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$



"unintegrated PDFs"

k_T dep. gluon plays prominent role at small x

rather direct access to saturation scale $Q_s(x)$
(e.g. through di-jet correlations in eA)

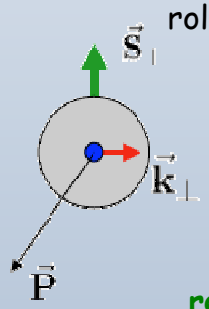


"Sivers effect"

access to 3D imaging in momentum space

non-trivial role of Wilson lines

role of spin-orbit correlations & OAM

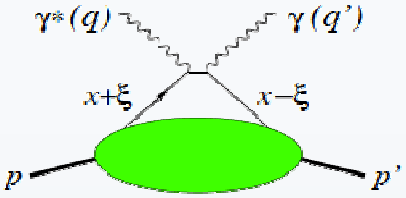


correlation of transverse spin of proton with k_T of unpolarized quark

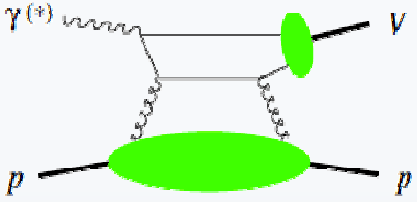
recent work by Z. Kang, J. Qiu

GPDs: access to transverse position

need to measure & study **exclusive processes:**

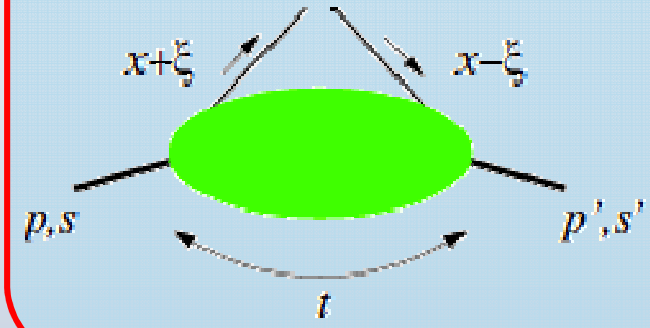


• deeply virtual Compton scattering (DVCS)



• exclusive meson production

• **generalized parton densities** (4 per flavor) needed to describe such processes:



GPDs depend on x, ξ, t, Q^2

convenient: symmetric choice of mom. fractions

• x, ξ: mom. fractions w.r.t. $P - \frac{1}{2}(p - p')$

where $\xi = (p - p')^+ / (p + p')^+$

in DVCS: x integrated and $\xi = x_B/(2 - x_B)$

• t: trade for trans. momentum transfer Δ

• GPDs represent interference between amplitudes for different nucleon states

• connection to energy-momentum tensor & OAM Ji

• equivalent to dipole model in "double limit" (small x, large Q^2)

transverse imaging @ eRHIC

- obtain GPDs from global analysis of DVCS & exclusive vector meson production

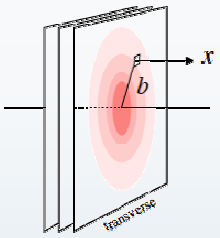
  framework already in place (used to analyze HERA & fixed target data) Muller, Kumericki, Passek-Kumericki

- perform Fourier transformation of GPDs to obtain b-space image

  e.g. $q(x,b^2) \sim \int d^2\Delta_\perp \; e^{ib\Delta} H^q(x,\xi=0,t=-\Delta^2)$ where $\Delta = p' - p$

  give

  center



exclusive processes experimentally very challenging

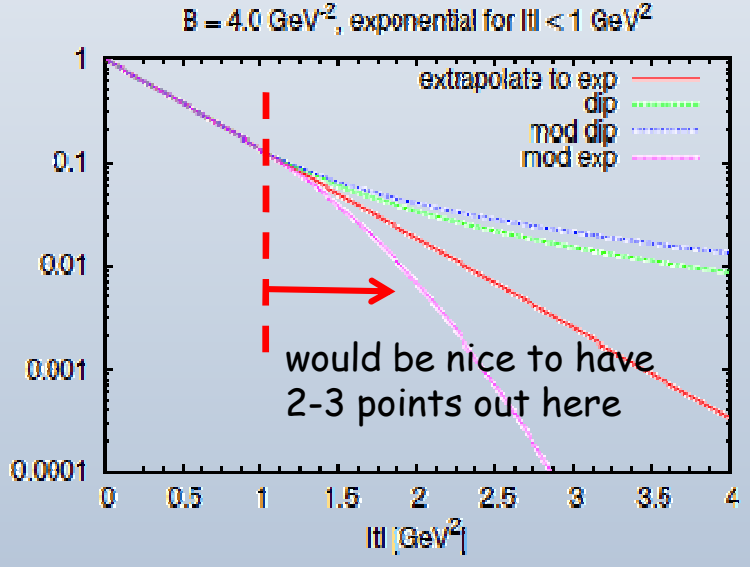
need to integrate Roman pots into IR design

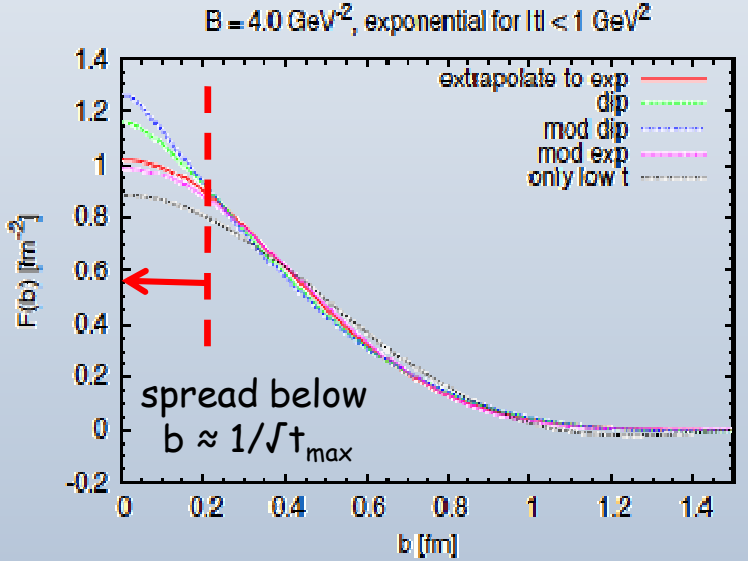
t acceptance vs magnet aperture & beam size

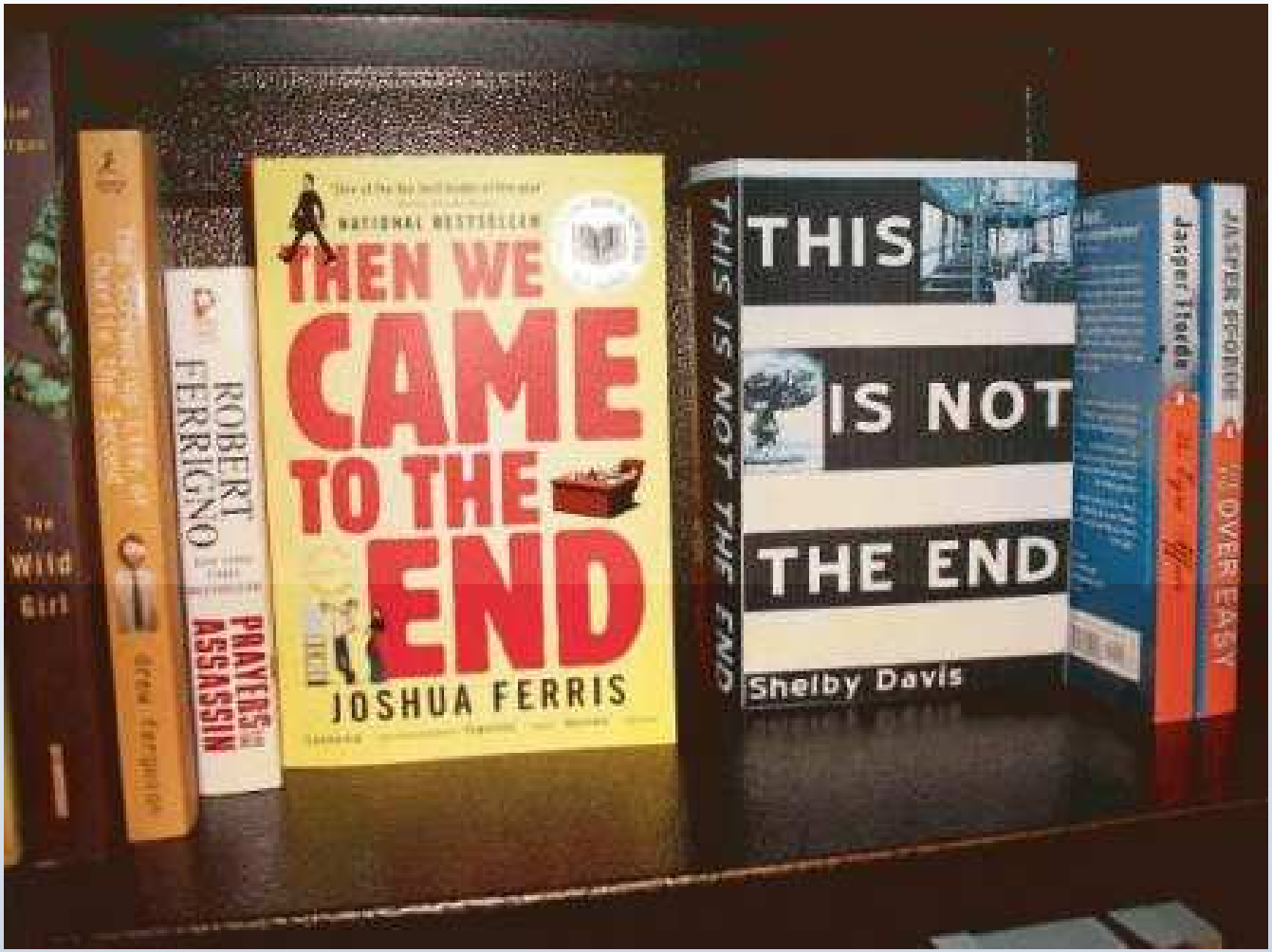
close collaboration between eRHIC TF & C-AD

- **challenge:**

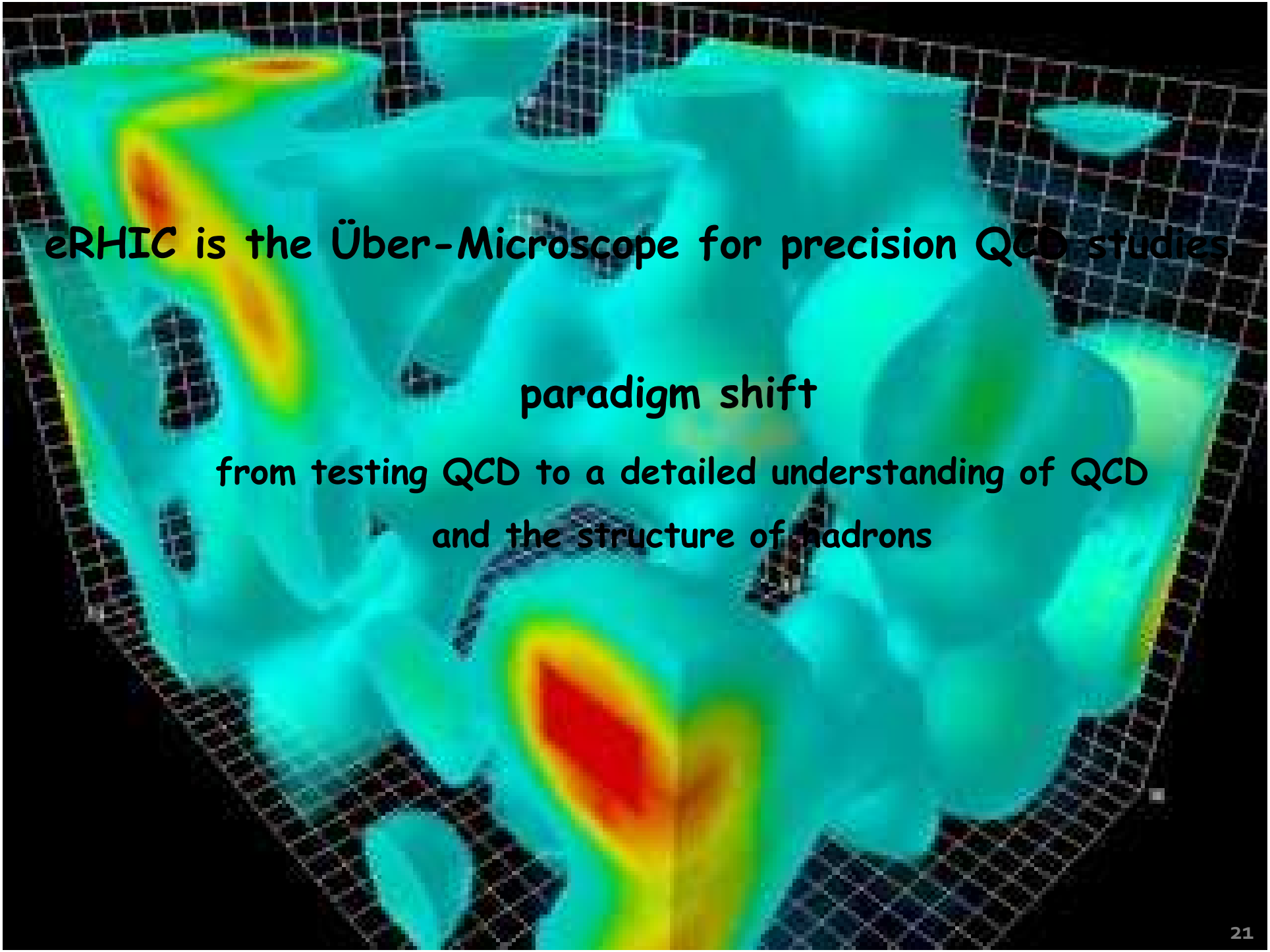
  extrapolation







Conclusions


eRHIC is the Über-Microscope for precision QCD studies
paradigm shift
from testing QCD to a detailed understanding of QCD
and the structure of hadrons